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OPERATION OF A LOW-VOLTAGE HIGH-TRANSCONDUCTANCE FILED EMITTER ARRAY TWT (BRIEFING CHARTS)

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CONFERENCE BRIEFING CHARTS

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Operation of a Low-Voltage High-Transconductance Field Emitter Array TWT

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Introduction

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- Implementation of "cold cathodes" as an electron source for RF vacuum devices can have a significant impact on many aspects of device operation

Cold Cathode Impact on RF Device Operation

- No Cathode Wearout Mechanism
- Room Temperature Operation
- Eliminate Heater Power
- High Current Density Operation
- Instant Turn-on
- Eliminate HV Modulator

- Multi-Mode Operation
- Infinite ON/OFF Isolation
- Device Miniaturization†
- Increased Interaction Efficiency†
- Improved Linearity†
- Decreased Harmonic Power†

†RF modulated cathode

Introduction

communications

Cold Cathode TWT History

- NEC Corporation
  - Late 1990s
  - Replaced thermionic cathode in X-Band TWT with Spindt-type cold cathode
  - 58 mA, 27.5 W, 10.5 GHz, 3% duty max (limited by TWT vacuum)
  - Focusing difficulties in first prototype – subsequently resolved
  - No recent activity

- Northrop Grumman Corporation
  - 1999 – 2002
  - C-Band cold cathode TWT
  - Single pulse up to 91 mA, 55 W, 4.5 GHz
  - 1% maximum duty factor at lower currents
  - 2002
  - RF-modulated cold cathode TWT
  - 5mA, 280mW, 6.75 GHz
  - No recent activity

- L-3 Communications – Electron Devices
  - 2007
  - C-Band cold cathode TWT
  - 30 mA, 18 W, 4.1 GHz, 1% duty
  - 10% duty at 10mA
  - 6 hrs lifetest at 1% duty, 2 hrs lifetest at 10% duty

Introduction

communications

L-3 Electron Devices Cold Cathode TWT Program

- Field emitter arrays have undergone a significant evolution in past several years, substantially reducing required operating voltages and potentially increasing life and reliability

- L-3 EDD has established a Vacuum Microelectronics Laboratory for testing of Cold Cathode Vacuum Devices

- A Field Emitter Array TWT test vehicle has been designed, fabricated and tested to evaluate the characteristics of the new low-voltage FEA cathodes and to characterize/optimize FEA TWT performance

Introduction

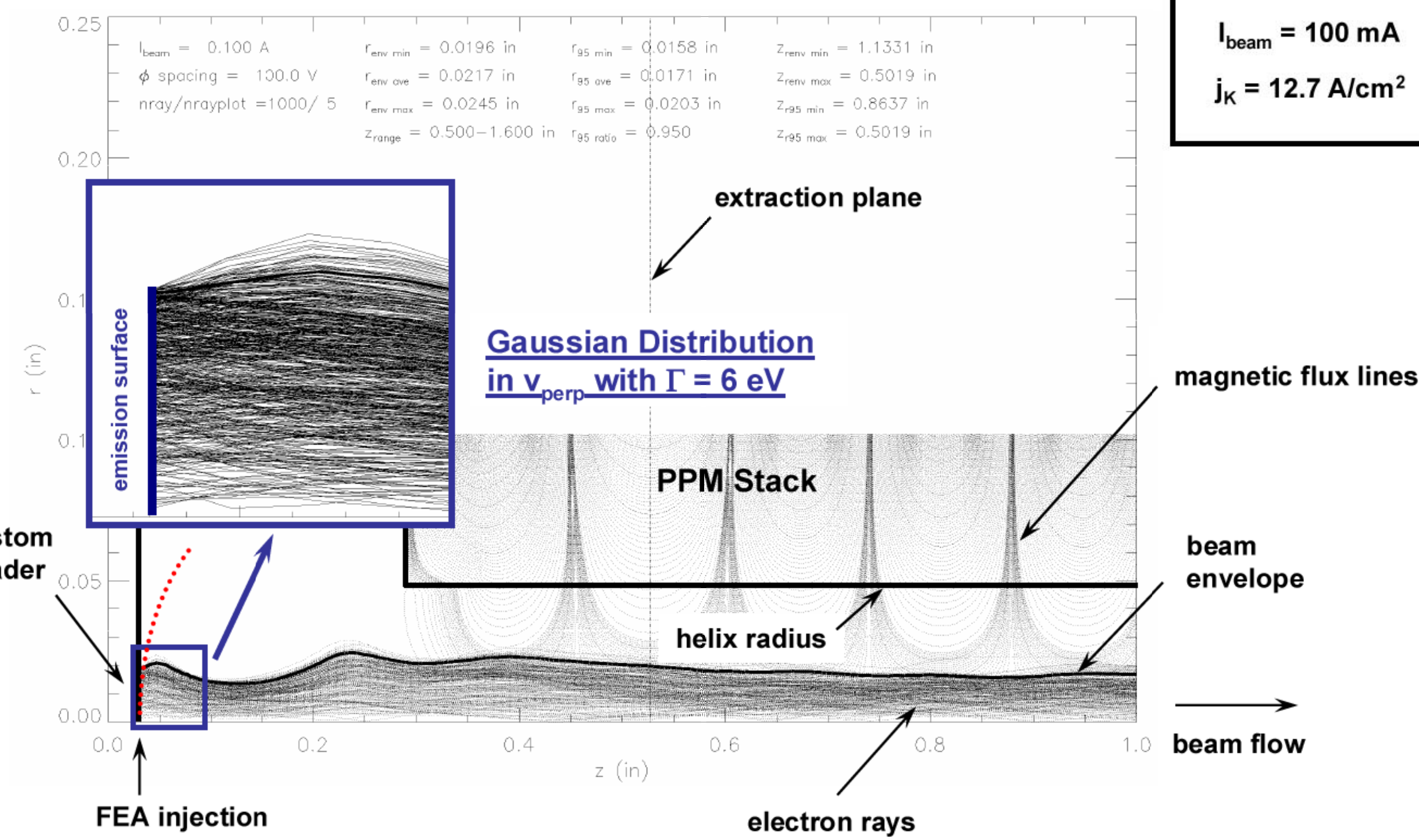
- Progress To Date
  - Built laboratory, integrated equipment and control system
  - Designed and fabricated electron gun capable of controlling high current density FEA electron beam
  - Integrated FEA cathode into TWT electron gun
  - Designed and fabricated TWT circuit/magnetics for
    - excellent beam control
    - high efficiency
    - wide bandwidth
    - moderate gain
  - Built prototype cold cathode TWT
  - Demonstrated performance exceeding all past measures of performance including beam current, cathode current density, total run time, duty factor, RF peak power, RF average power
  - Performed life tests, cold cathode processing in TWT environment, noise measurements

Simulation

Electron Optics

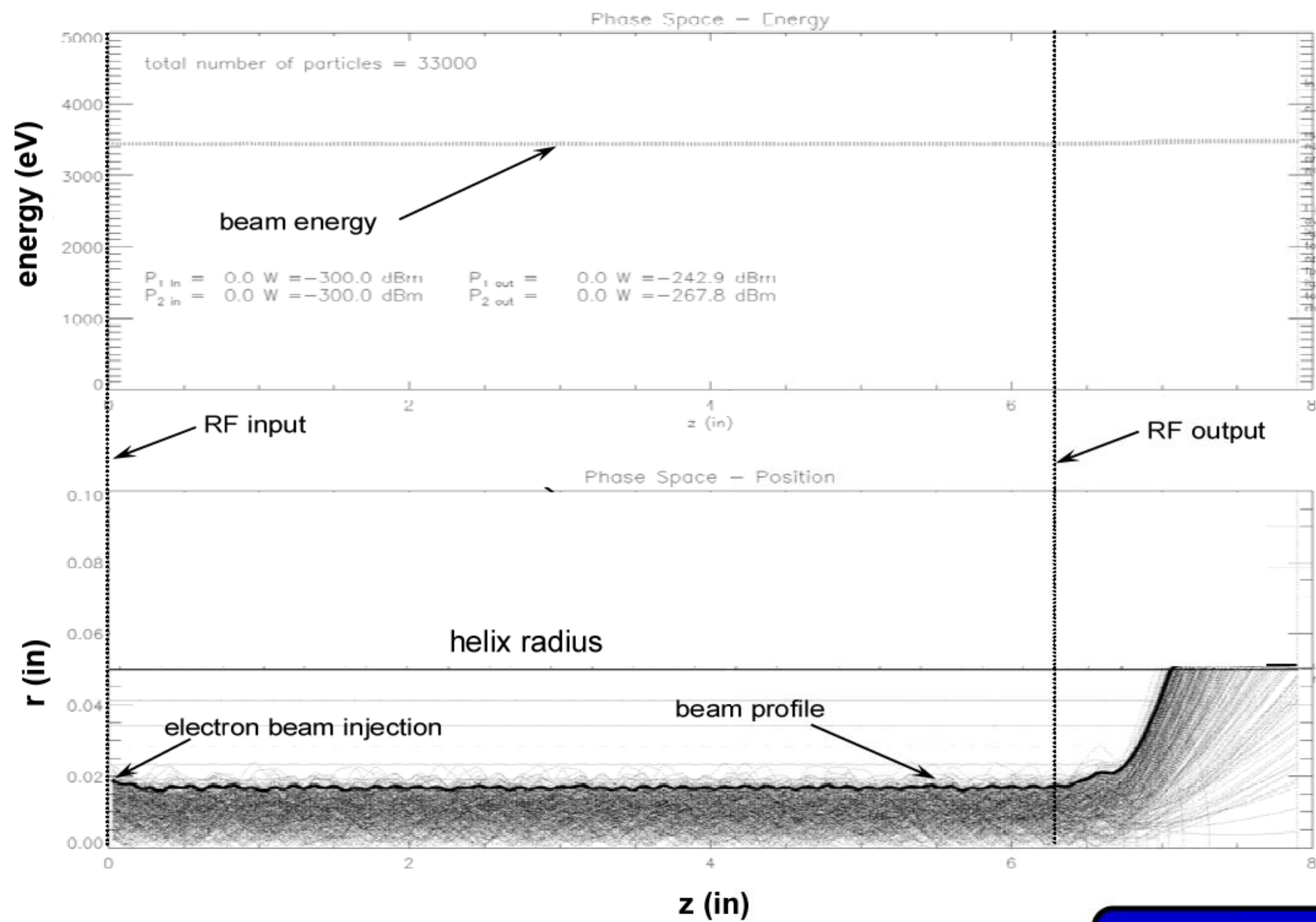
I_{beam} = 100 mA

j_K = 12.7 A/cm^2



Simulation

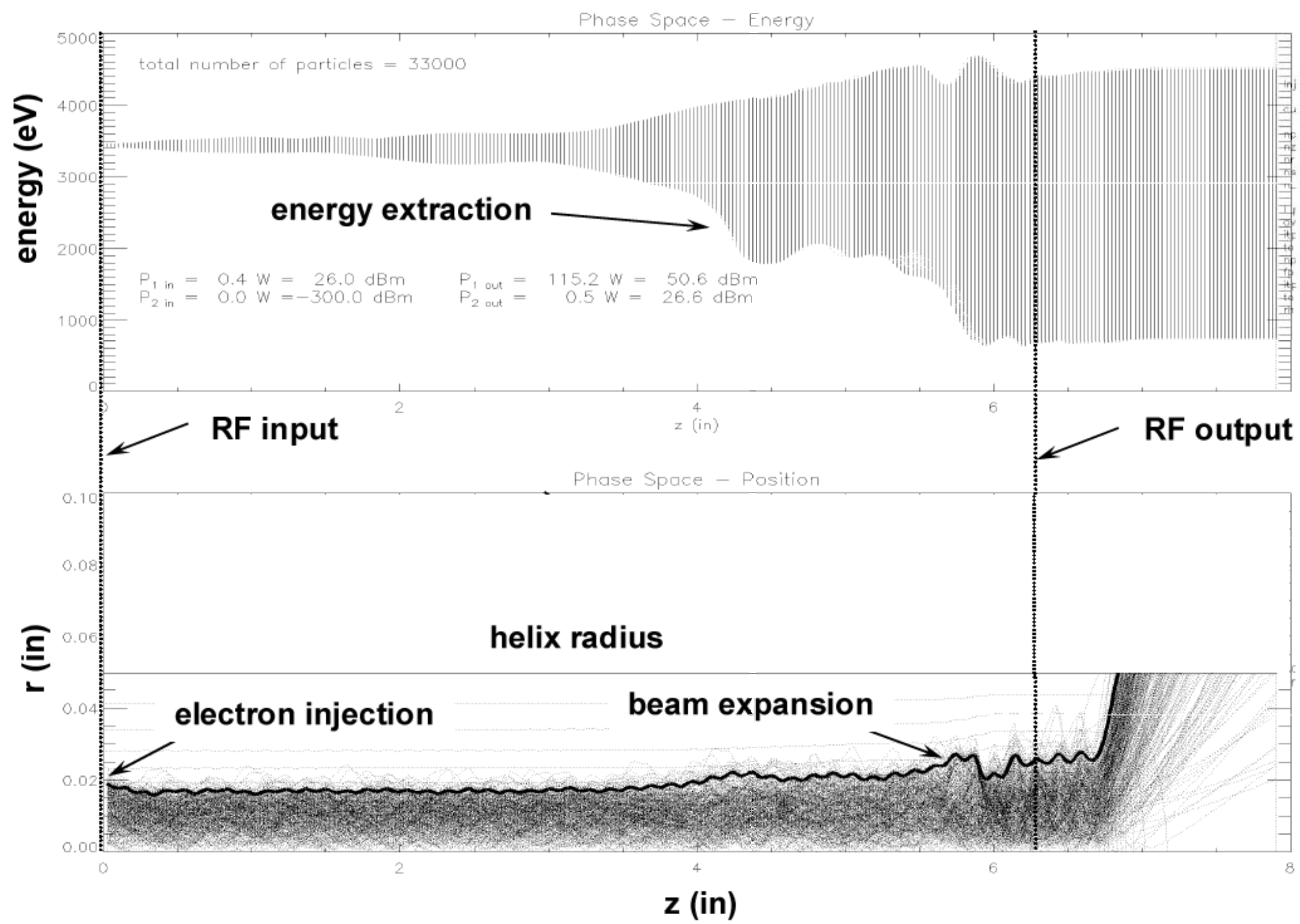
CHRISTINE3D Interaction Simulation – No RF Drive



$N_{particles} = 33000$

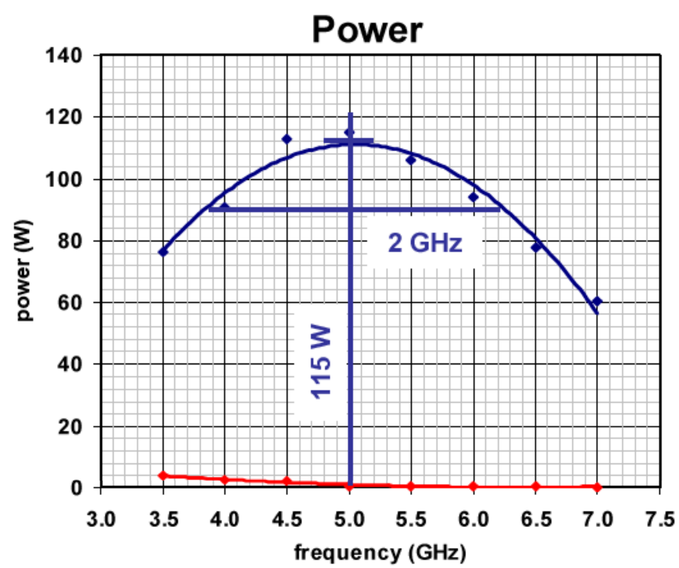
Simulation

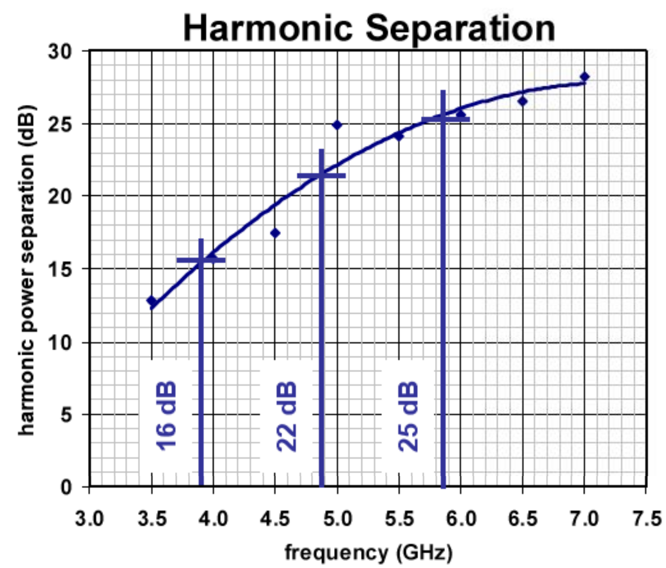
CHRISTINE3D Interaction Simulation – Saturated, Band Center

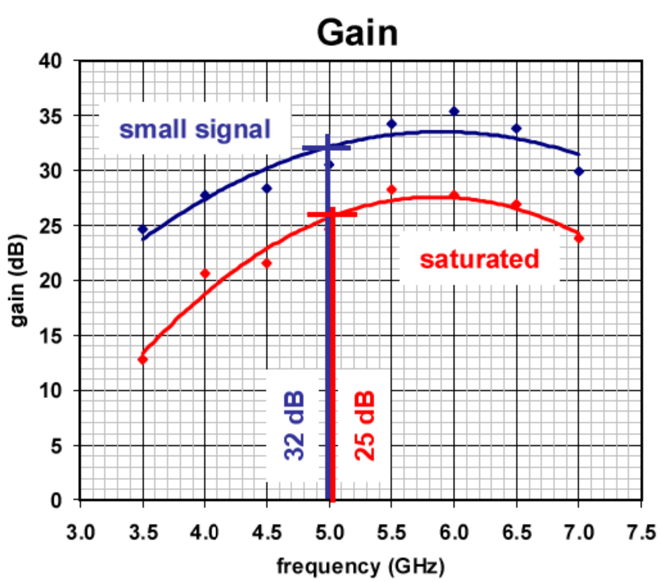


P_{RF} = 115W

Simulation



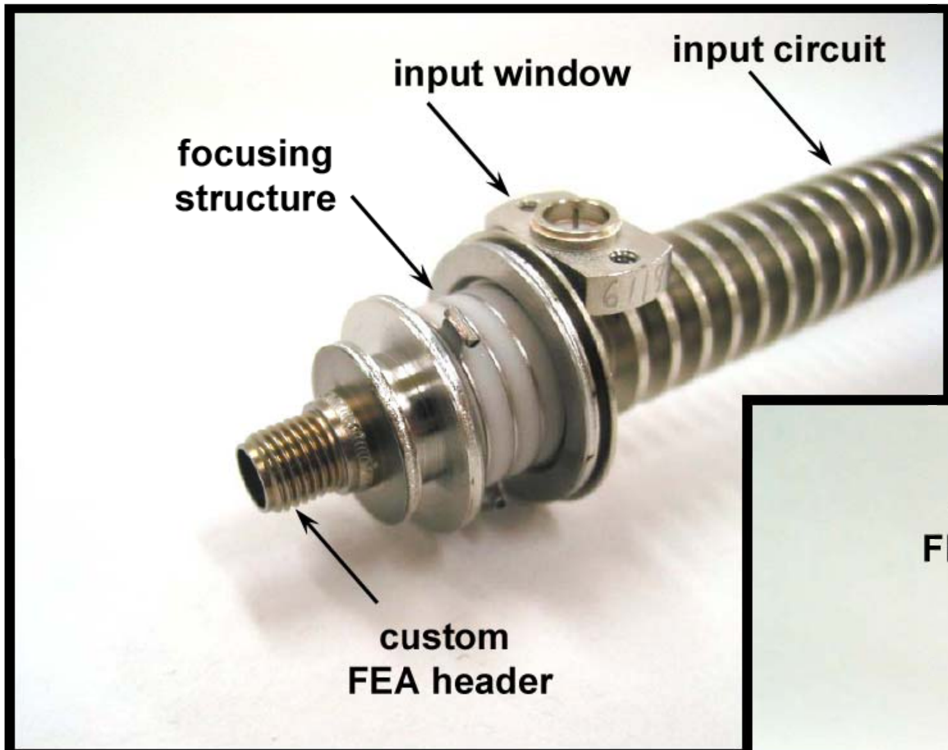


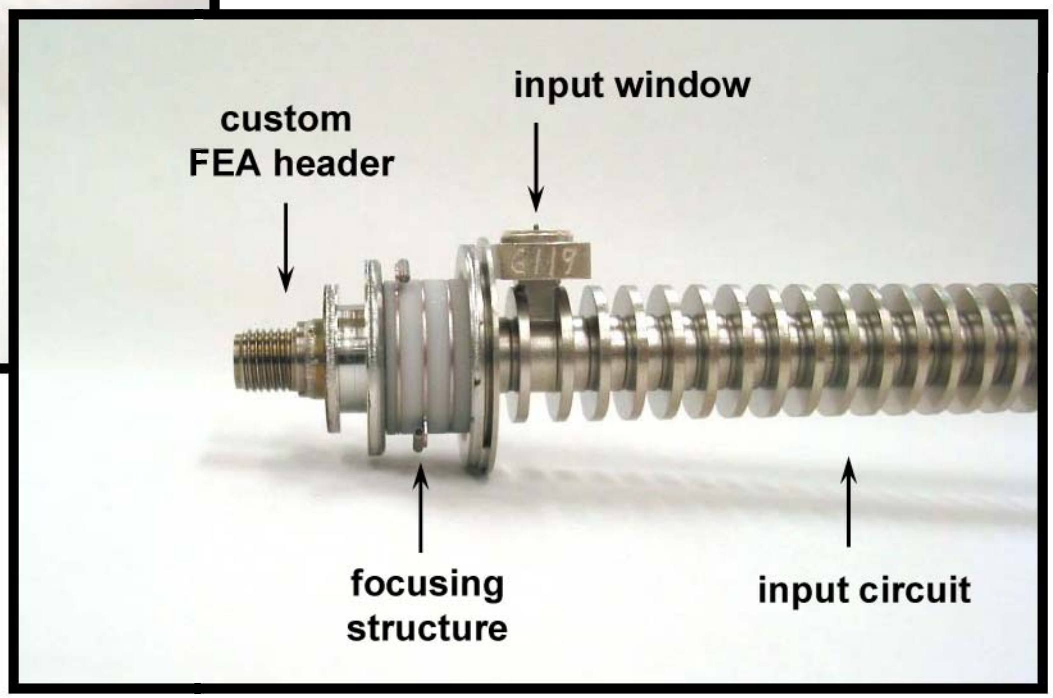


I_{beam}	100 mA
V_{beam}	3500 V
Sat Power	115 W
SS Gain	32 dB
Sat Gain	25 dB
$\eta_{circuit}$	32 %
1 dB B/W	2 GHz
3 dB B/W	4 GHz

Hardware

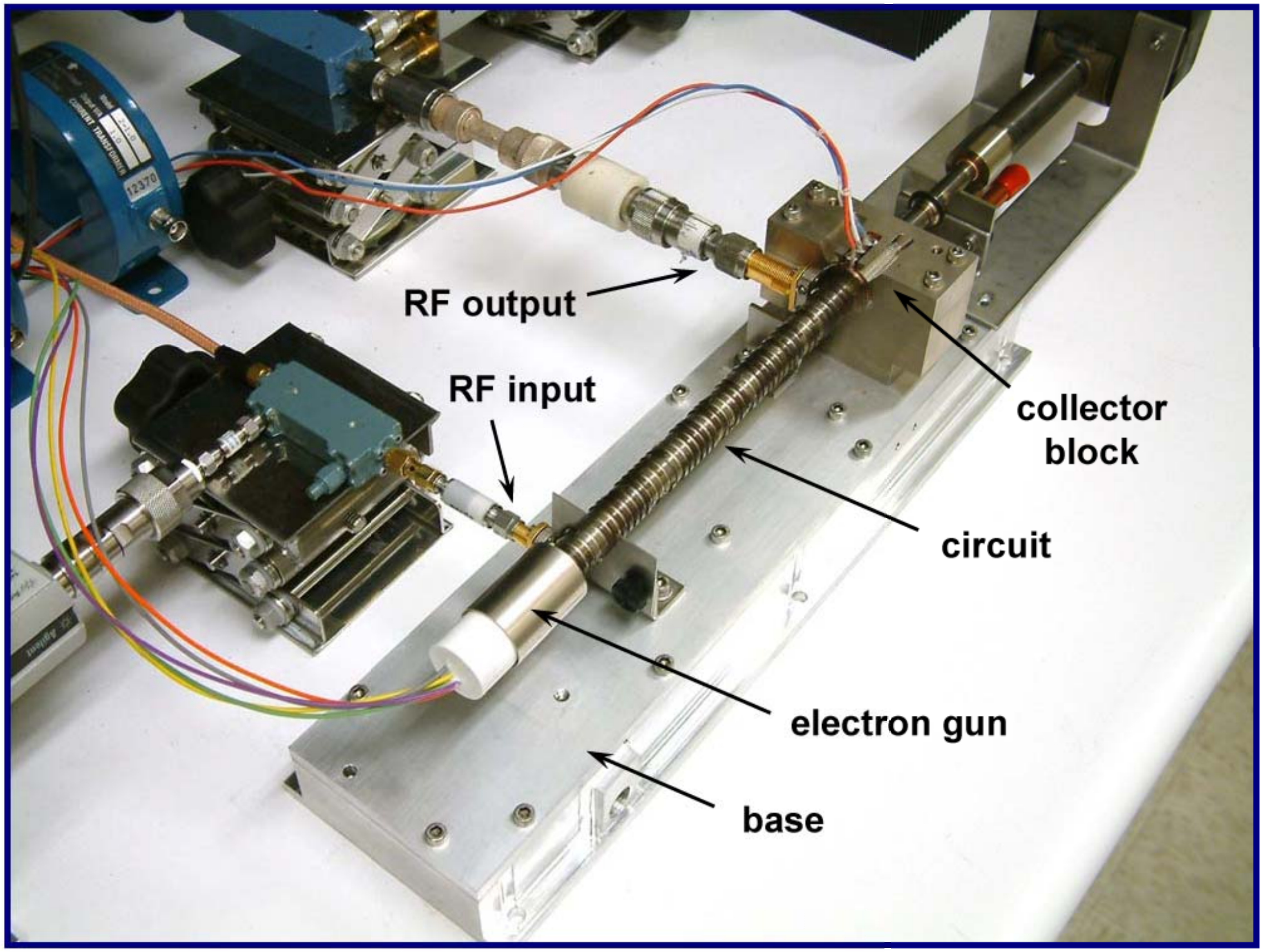
Prototype #1 – Pre-Exhaust





Hardware

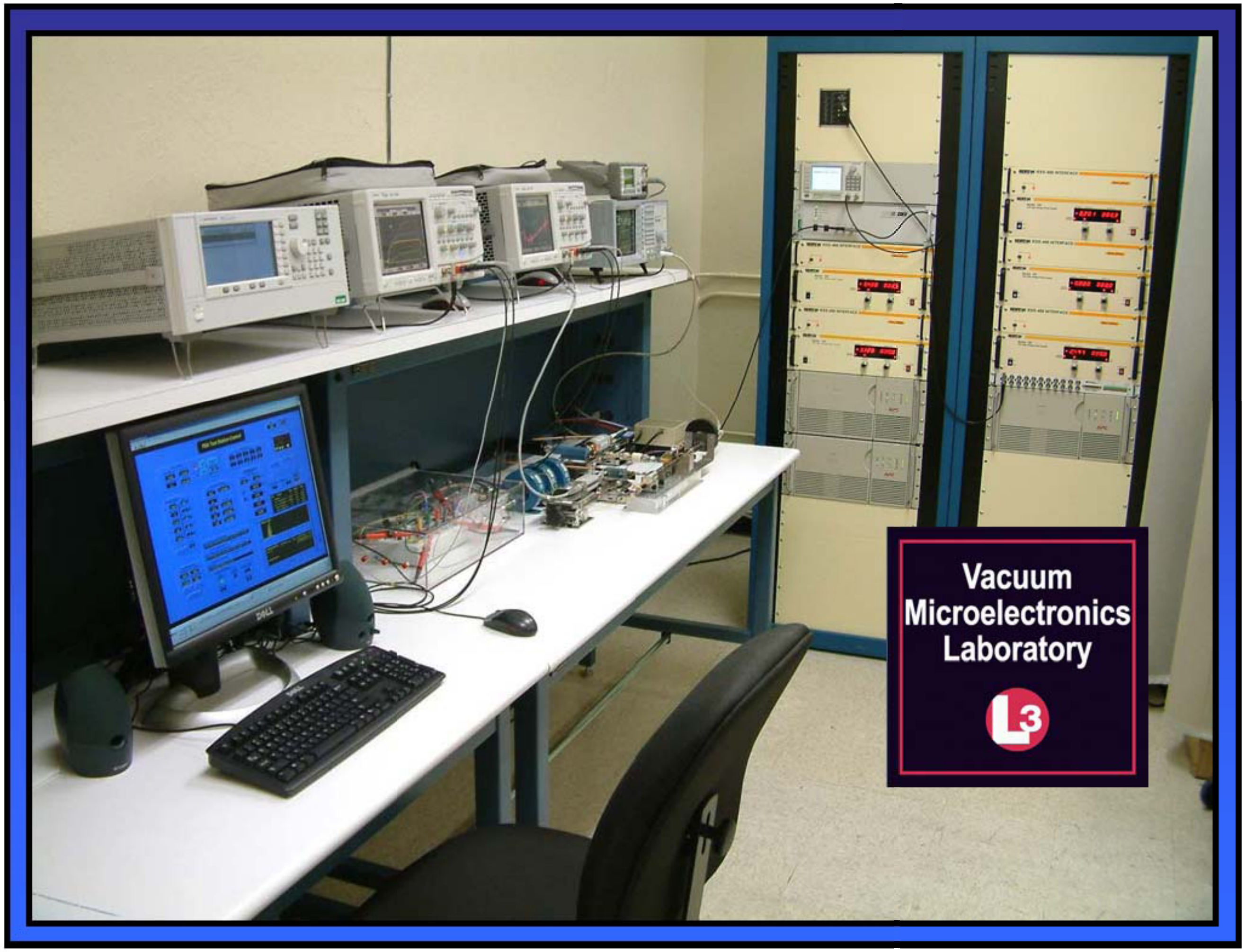
Final Experimental Configuration – Prototype #1



SRI Emitter Characteristics

diameter	1 mm
tip number	50,000
tip material	Molybdenum
a_{FN}	0.030 A/V^2
b_{FN}	490 V

Laboratory



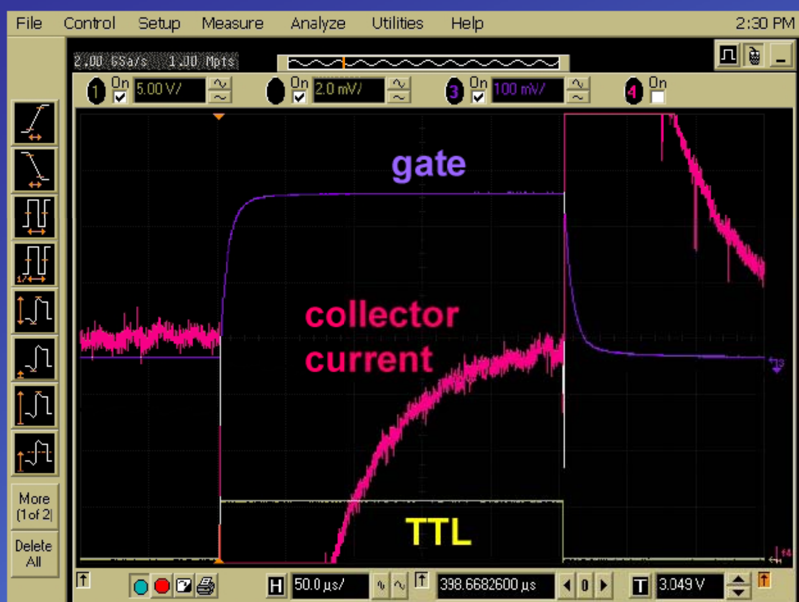
Vacuum Microelectronics Laboratory

- Established for Test of Cold Cathode RF Vacuum Devices
- Dedicated Equipment
- Fully Functional
- Computer Controlled
- Life Test System Operational

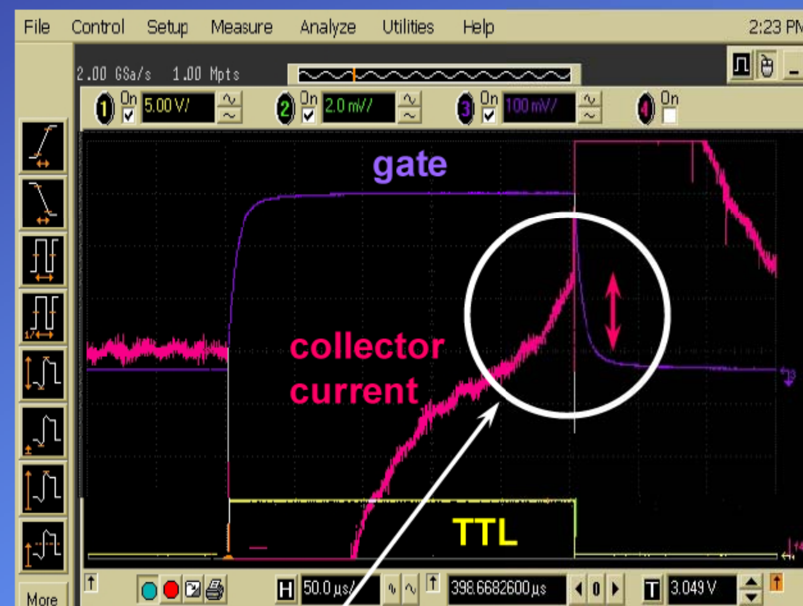
Experimental Results

Low Turn-on Voltage

V_{gate} = 21 V



V_{gate} = 23 V

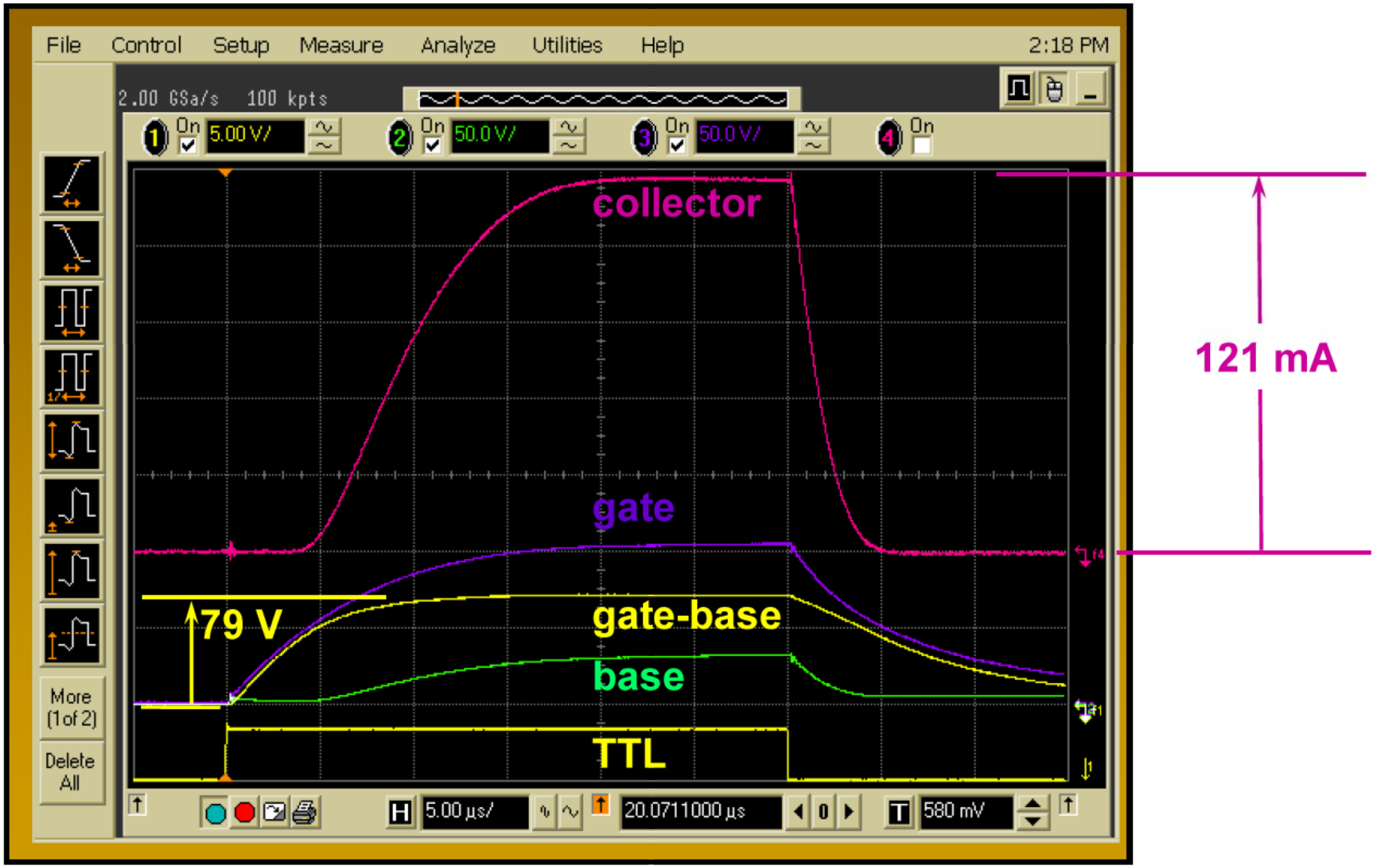


FIRST MEASURED
FEA TWT CURRENT AT 23 V

↕ = 1 nA

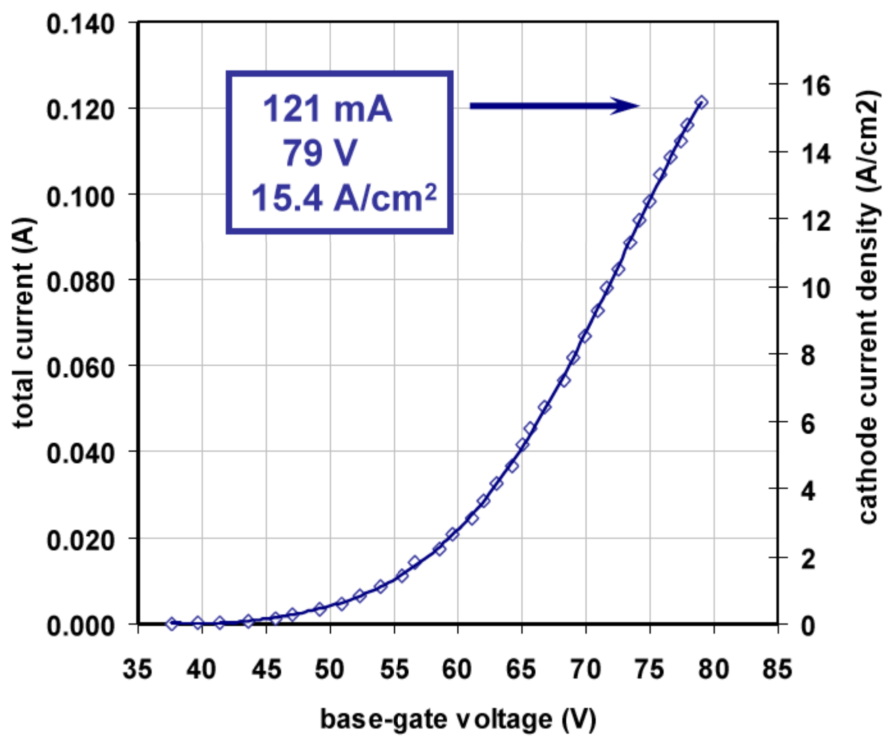
Experimental Results

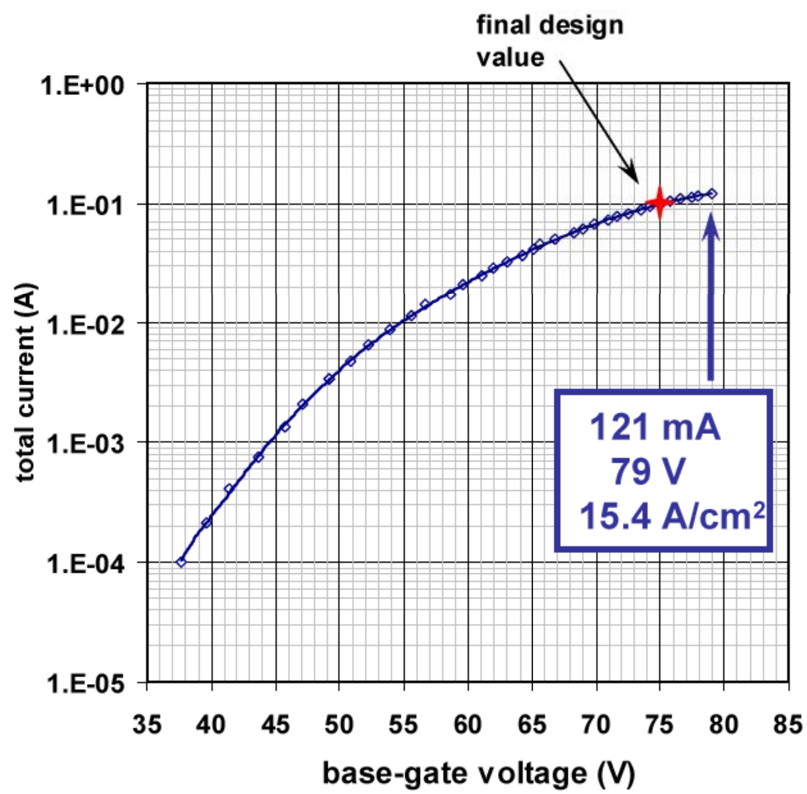
Typical Waveforms



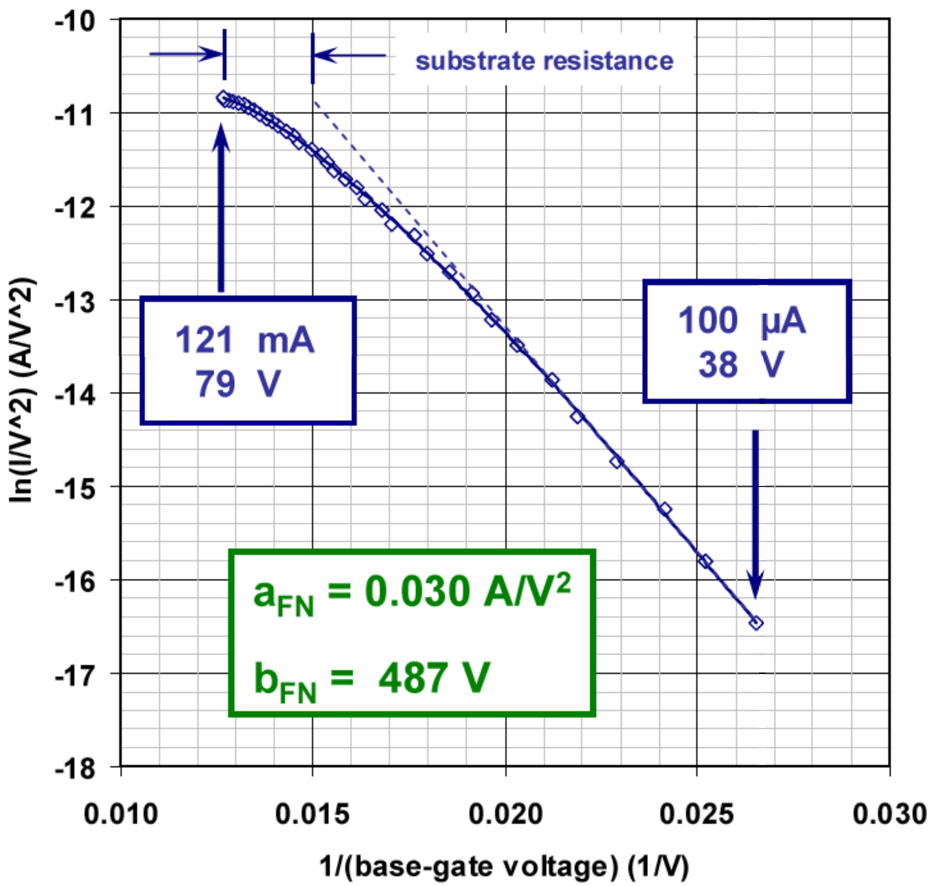
Experimental Results

Measured FEA Emission vs. Base-Gate Voltage





Experimental Results



Fowler Nordheim Emission

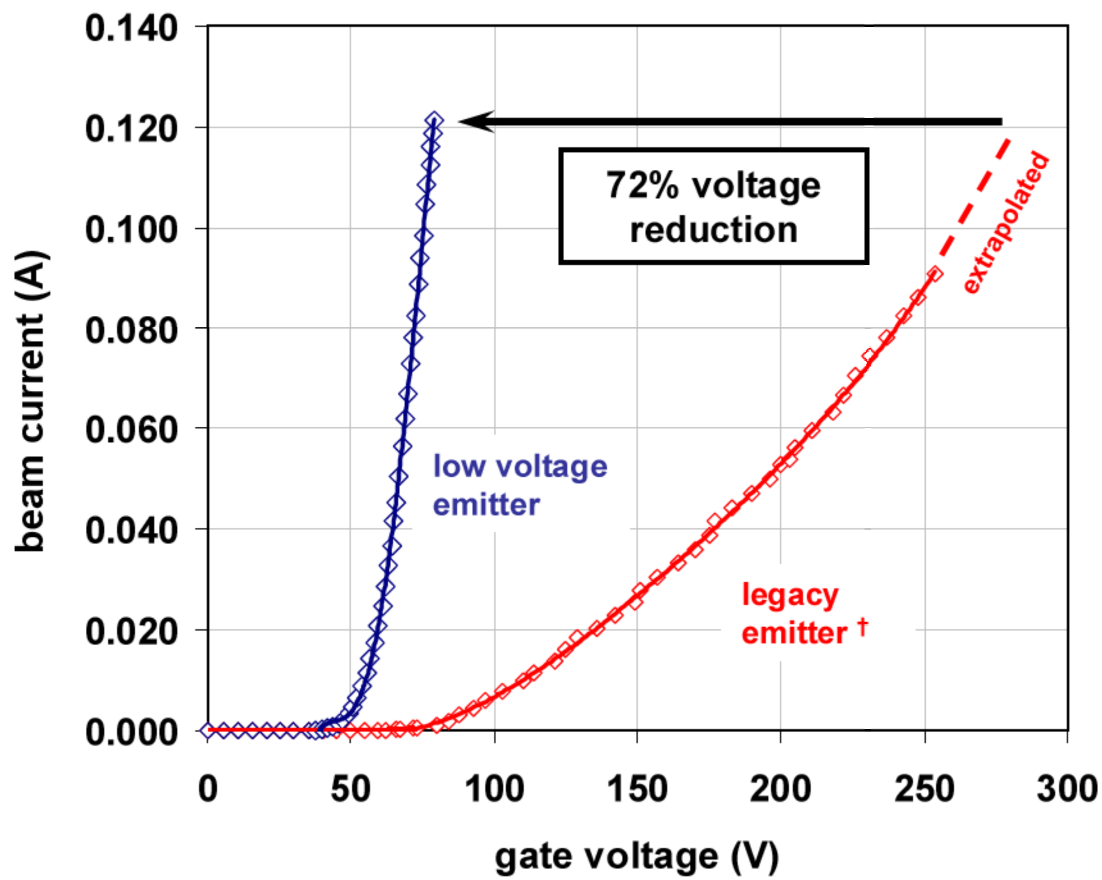
$$I = a_{FN}\, V_{BG}^2 \exp\left(-\frac{b_{FN}}{V_{BG}}\right)$$

$$\ln(I / V_{BG}^2) = \ln(a_{FN}) - \frac{b_{FN}}{V_{BG}}$$

Experimental Results

communications

Operating-Voltage Reduction with New Low-Voltage Emitters



At maximum current

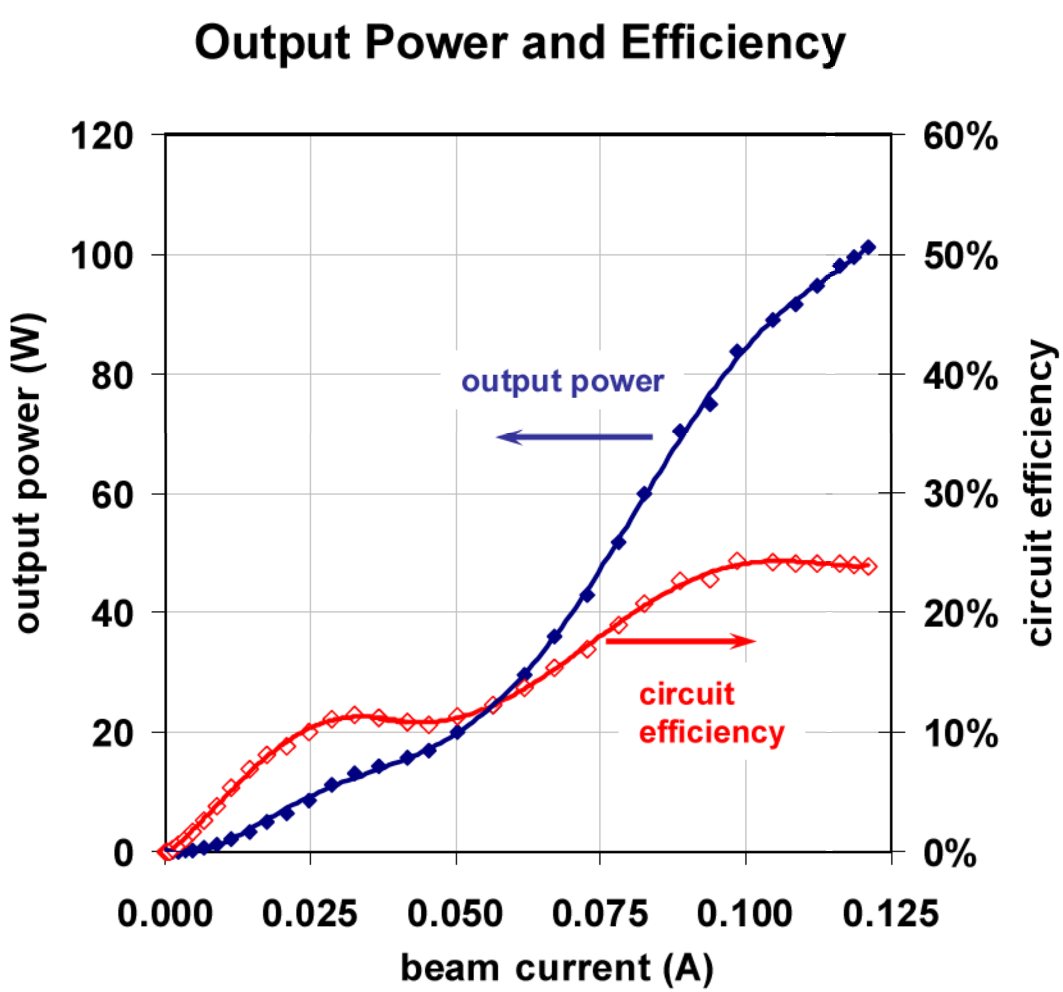
$V_{\text{low voltage}} = \underline{79\ V}$

$V_{\text{legacy}} = \underline{280\ V}$

$$\frac{V_{\text{low voltage}}}{V_{\text{legacy}}} = 0.28$$

† D. R. Whaley, et al., *IEEE Trans. on Plasma Science*, Vol. 28, No. 3, p. 727-747 (2000).

Experimental Results

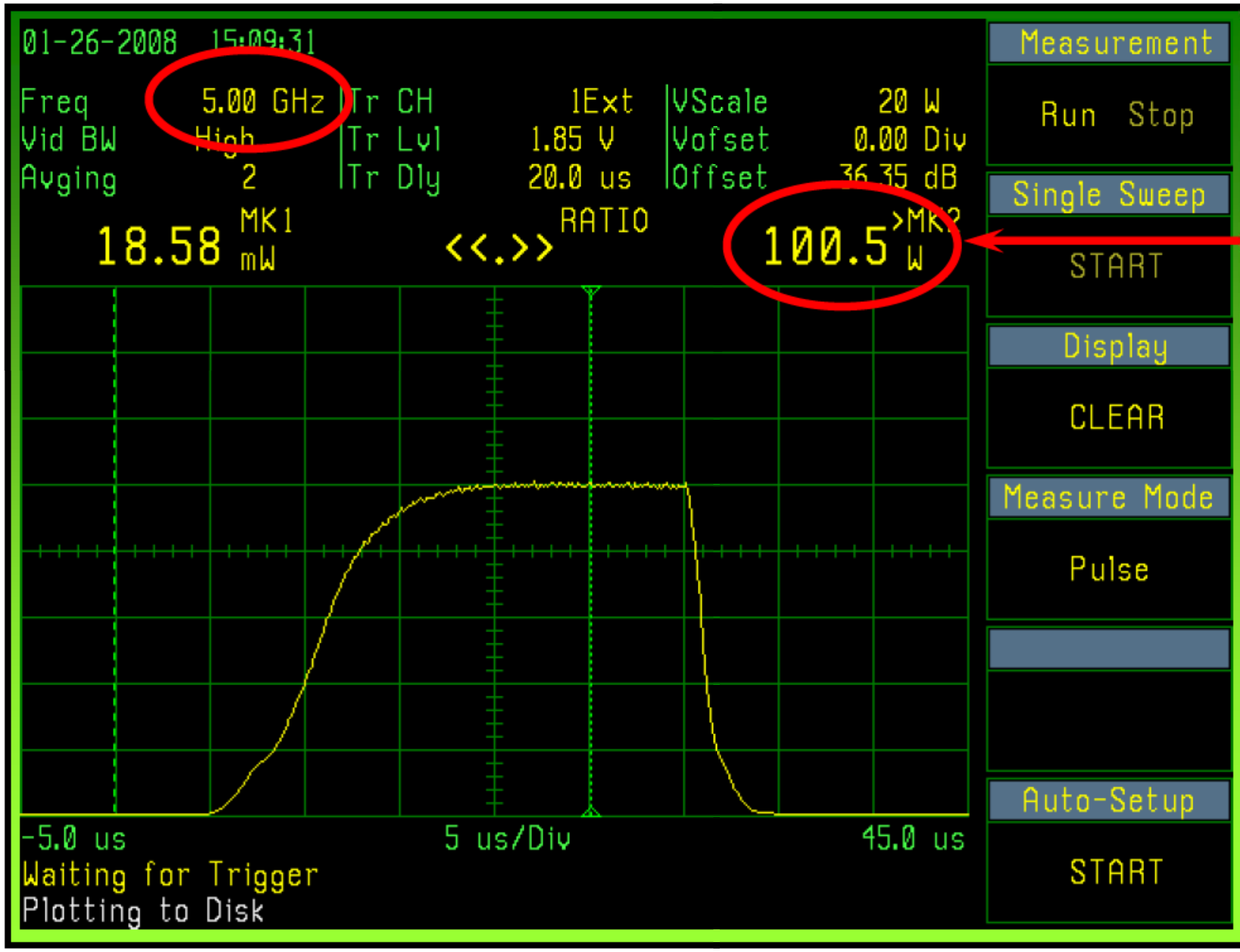


At maximum current

V_{beam}	3500 V
I_{beam}	120 mA
Frequency	5.0 GHz
Small Signal Gain	32.7 dB
Sat Power	100 W
Sat Gain	22.1 dB
Circuit Efficiency	24 %

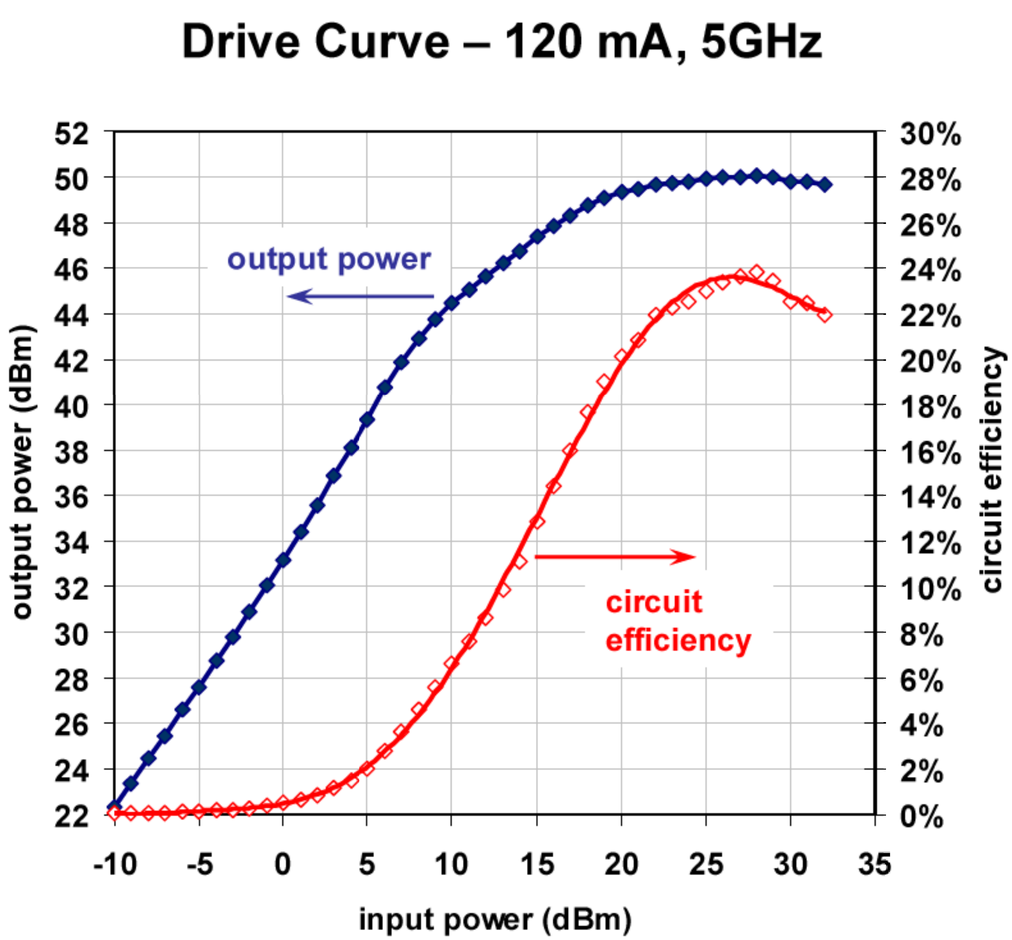
Experimental Results

Peak Power Analyzer – 120 mA



100.5 W
50.0 dBm
5.0 GHz

Experimental Results



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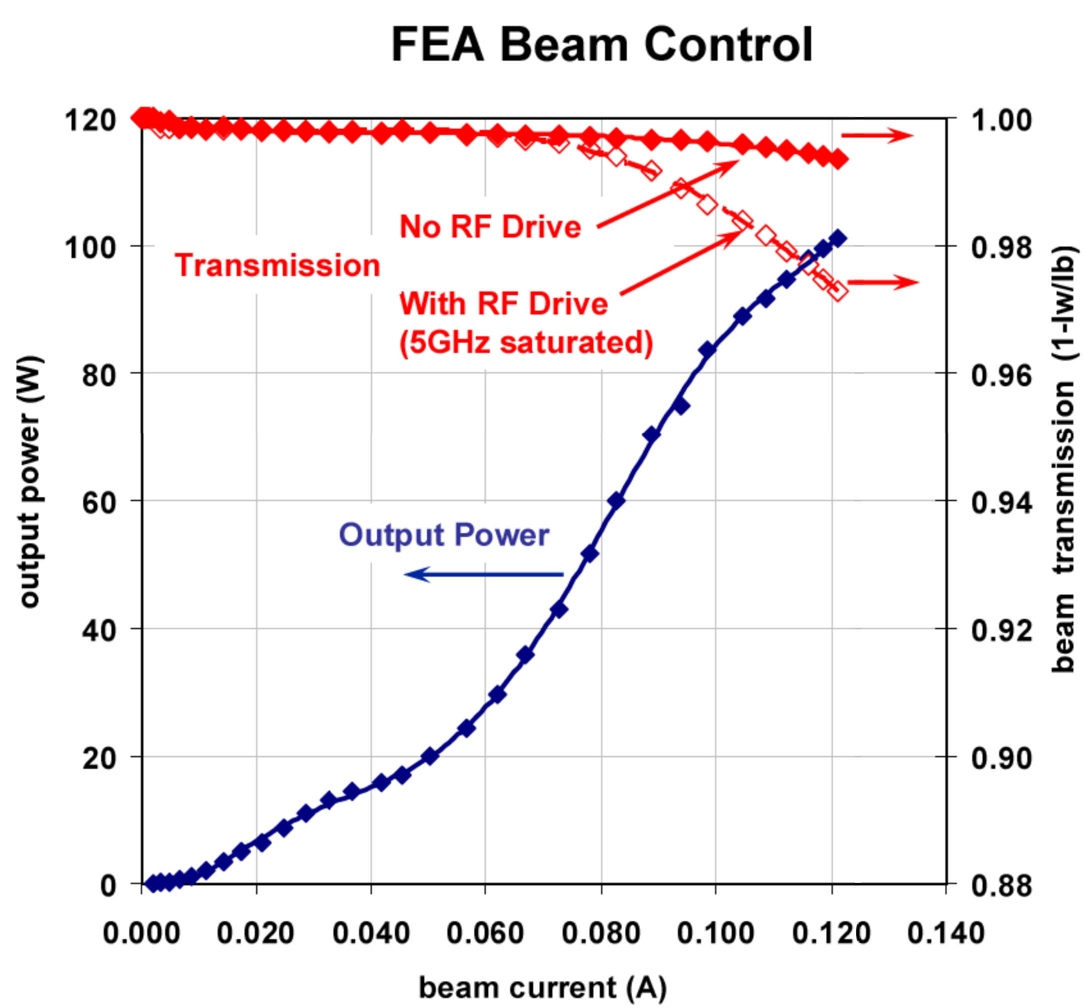


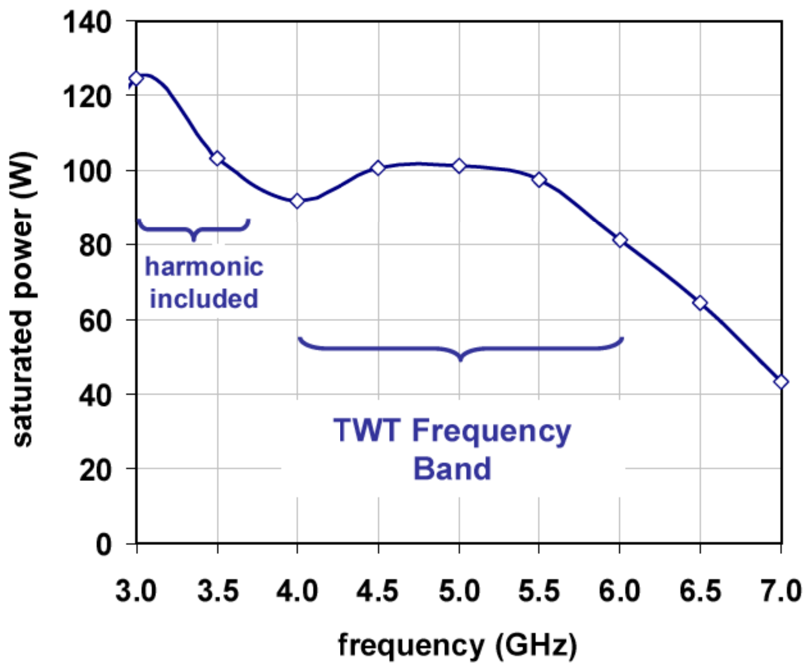
Beam Transmission

No RF Drive – 99.4%

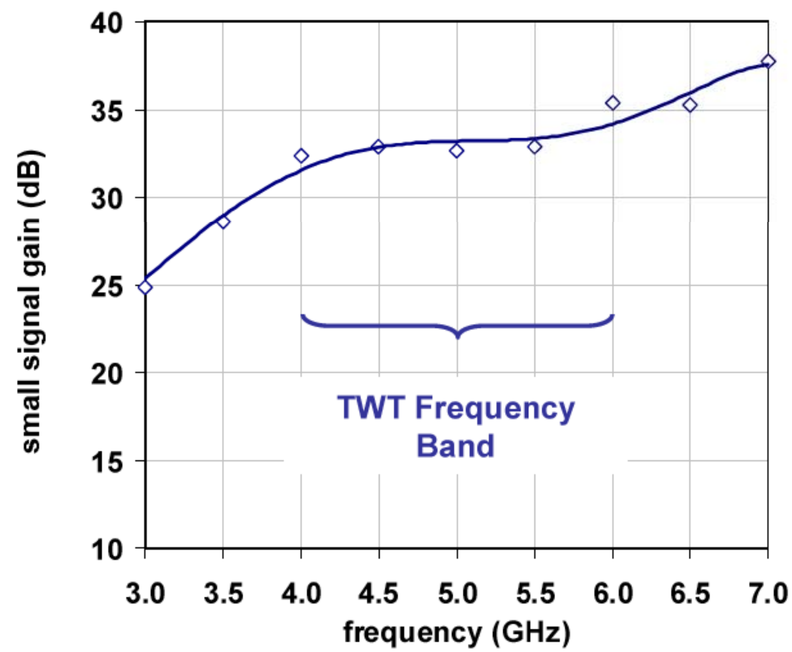
Sat RF Drive – 97.3%

Experimental Results

Saturated Power

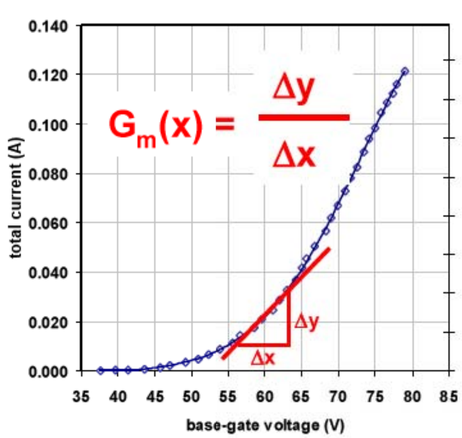


Small Signal Gain



Transconductance

- $G_m = dI/dV_{b\text{-}g}$
- Local slope of I/V curve
- Measure of current emission sensitivity to applied voltage
- Changes with applied voltage and emission current
- Measured in Siemens or A/V



High Transconductance Cathodes

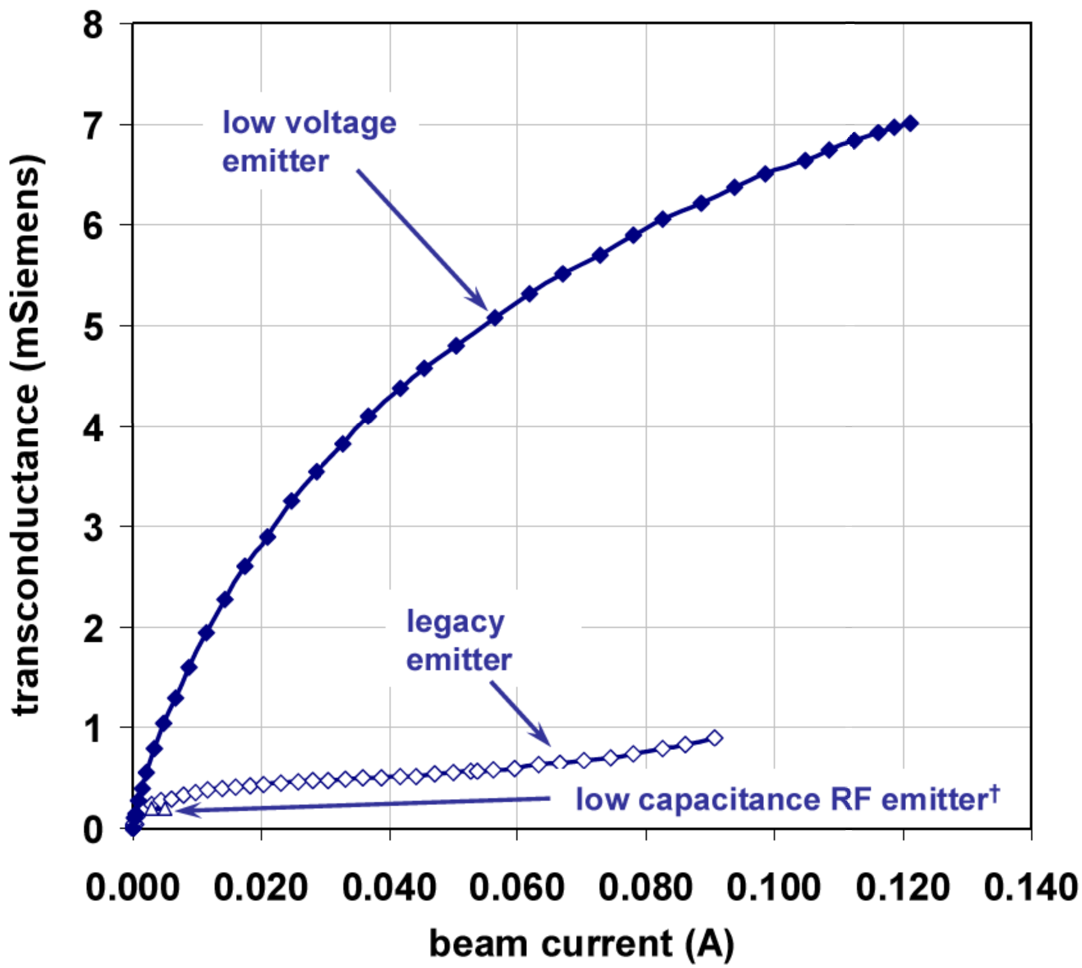
Advantages

- Generally means low turnon voltage and low operating voltage
- Low cathode electrical stress
- Low gate surge currents and gate heating during high PRF pulsed operation
- RF-modulated operation possible
- Offsets low capacitance requirement for RF modulated operation

Disadvantages

- Current emission sensitive to power supply drift
- Power supply ripple can generate carrier sidebands due to unintended baseband current modulation

Experimental Results



Emitter Type	max G_m
RF Modulated	0.20 mA/V
Legacy	0.89 mA/V
Low Voltage	7.01 mA/V

† D. R. Whaley, et al., *IEEE Trans. on Plasma Science*, Vol. 30, No. 3, p. 998-1008 (2002).

Experimental Results

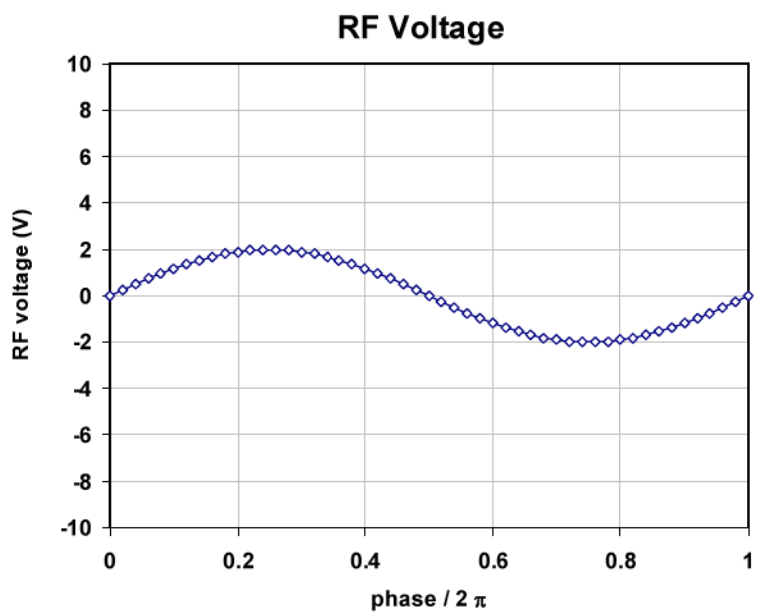
communications

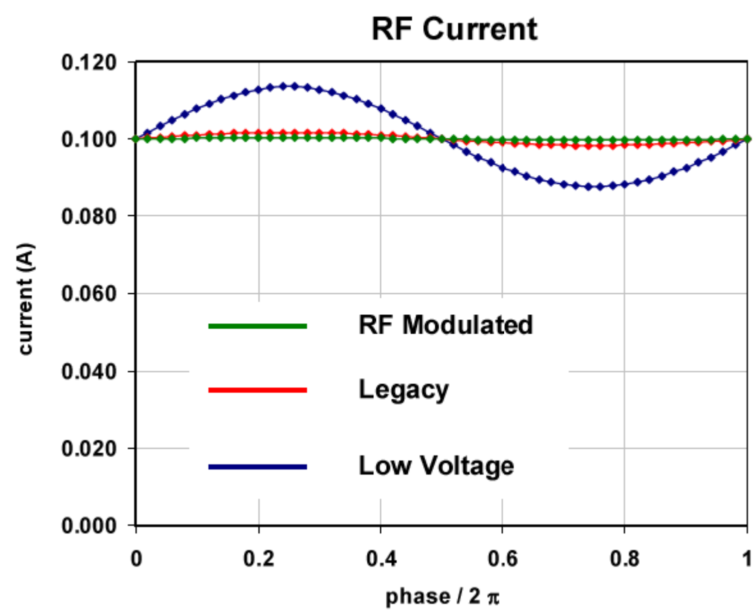
- **High Transconductance Can Offset Need for Low Capacitance in RF Modulated Cathodes**

$$Modulation\ Efficiency = \frac{\Delta I_{RF}}{I} \propto \underbrace{\frac{\partial I}{\partial V}}_{\text{transconductance}} \times \underbrace{\Delta V_{RF}}_{\text{inversely with capacitance}}$$

transconductance

inversely with capacitance

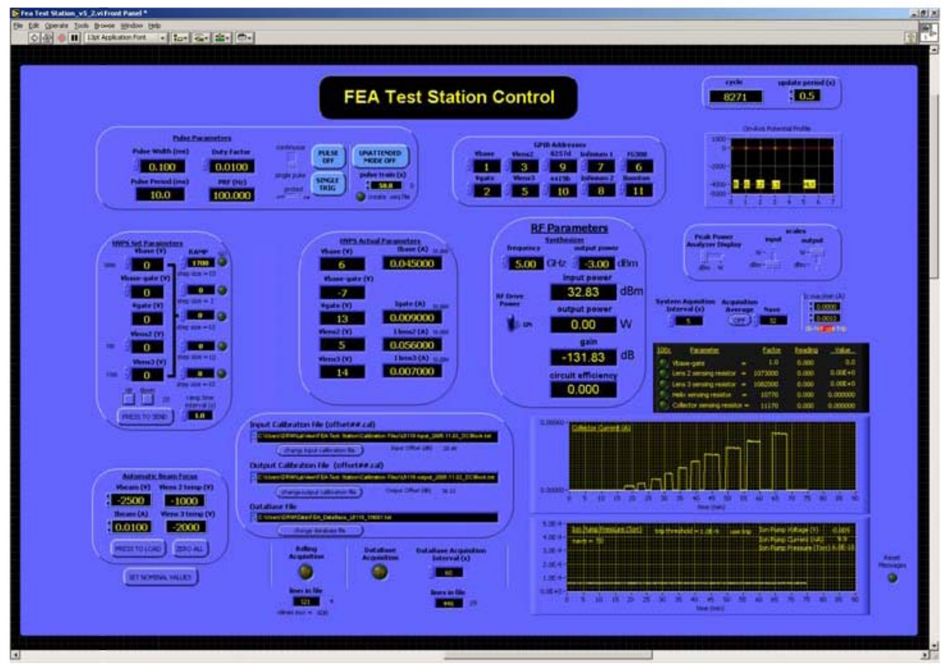




Experimental Results

Life Tests

- LabView data control and acquisition system records all TWT operating parameters vs. time
  - time stamp
  - pulse parameters (pulse width, duty factor)
  - base voltage
  - gate voltage
  - gun lens voltages
  - gun lens currents
  - helix current
  - collector current
  - RF input power
  - RF output power
  - vacuum pressure



Experimental Results

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<u>Life Test Summary</u>

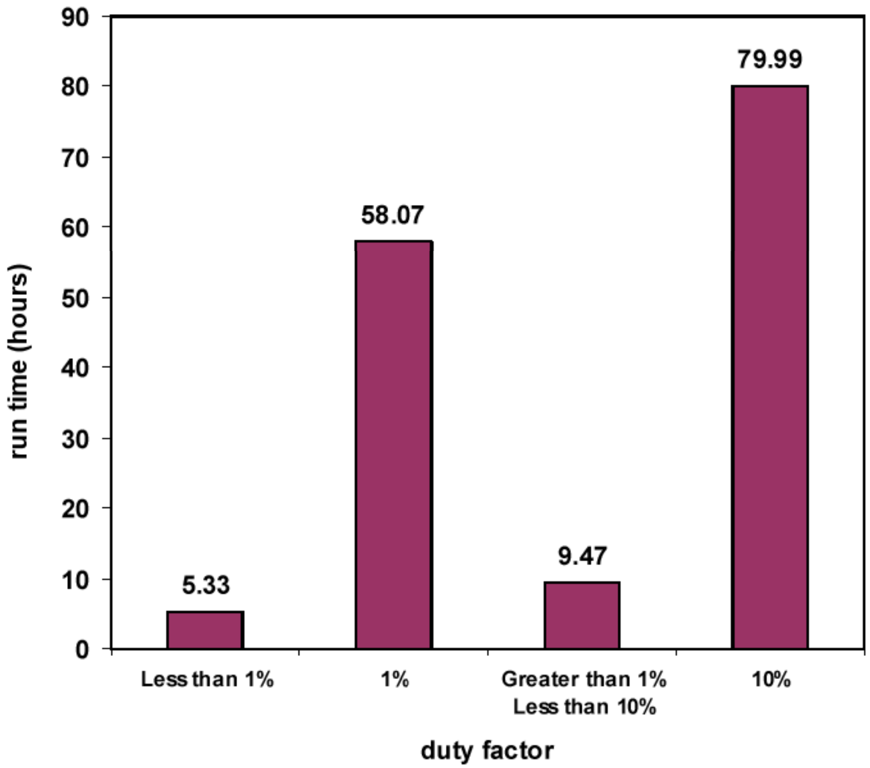
- 10% Duty Operation at 10mA, 20mA, 40mA, 60mA, and 80mA
- 1% Duty Operation at 100mA (85W)
- Single pulsing up to 120mA (100W)

- Total 1% Duty Pulse Time – 58 hours
- Total 10% Duty Pulse Time – 80 hours
- Total Pulse Time – 153 hours

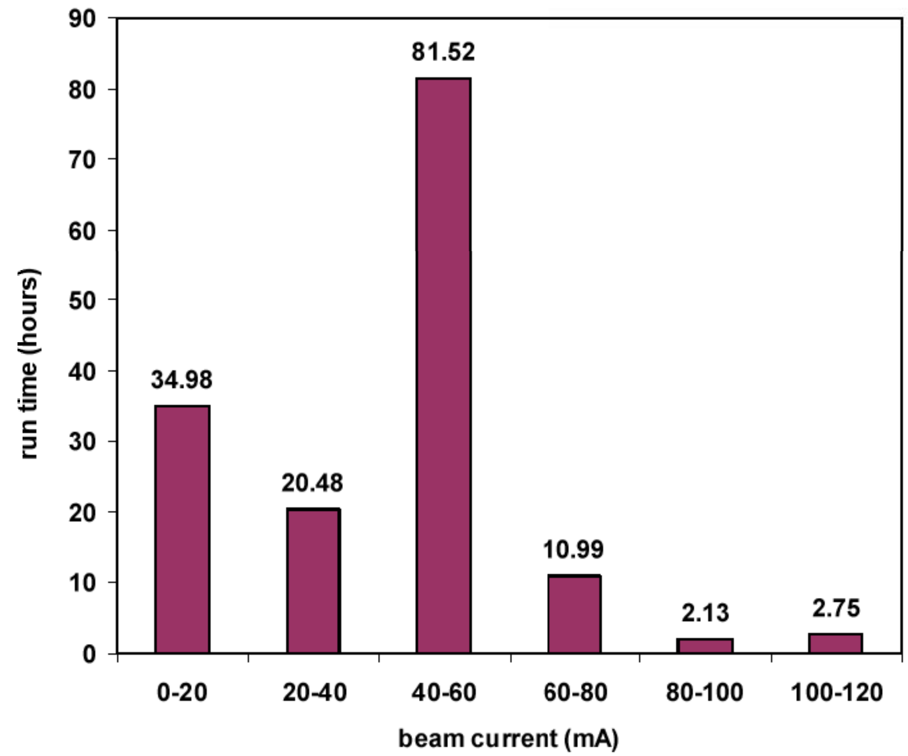
- Total Number of Database Points – 56 k
- Total FEA Pulses – 826 M

Experimental Results

Duty Factor

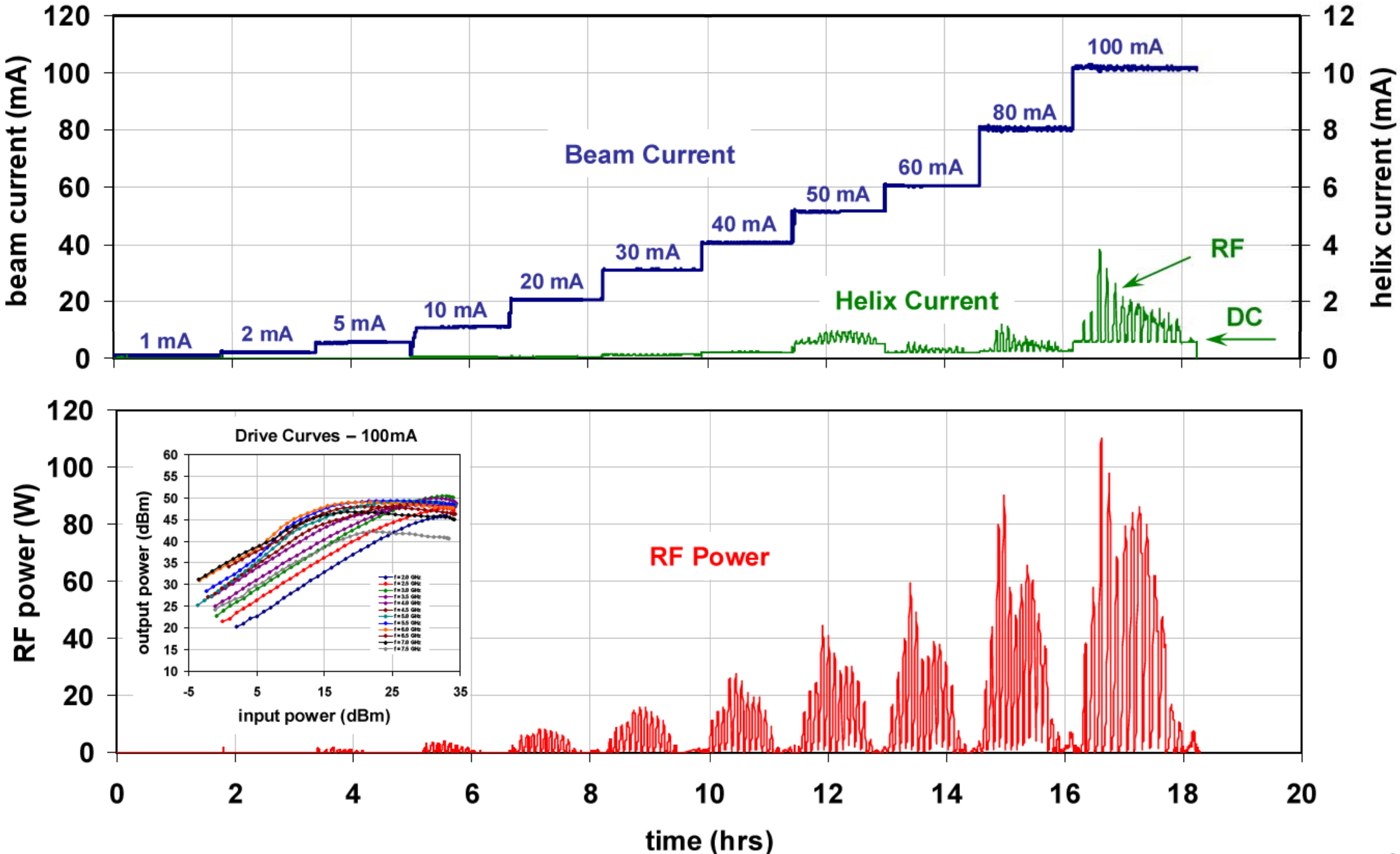


Beam Current (Peak)



Experimental Results

Device Characterization



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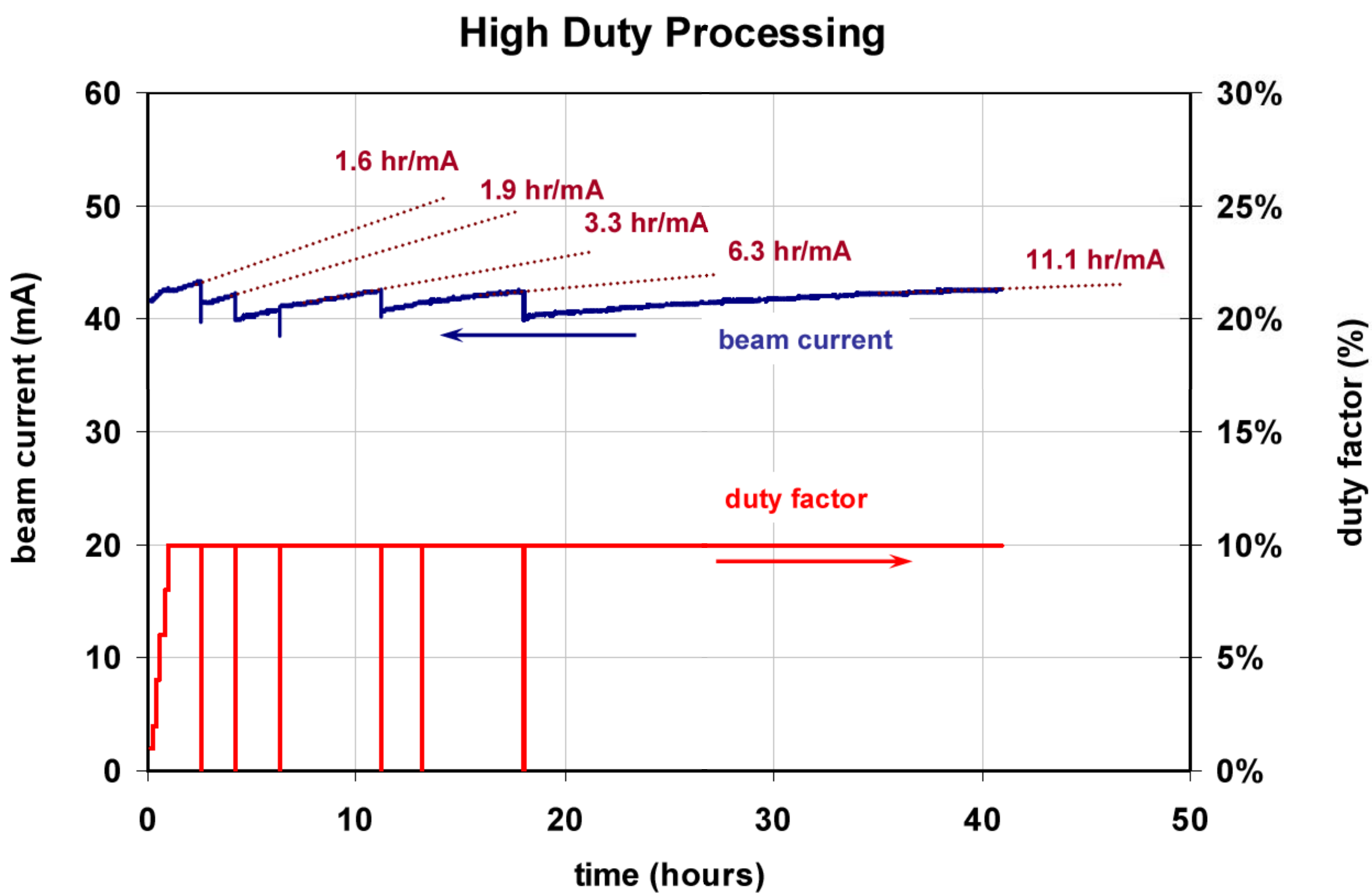
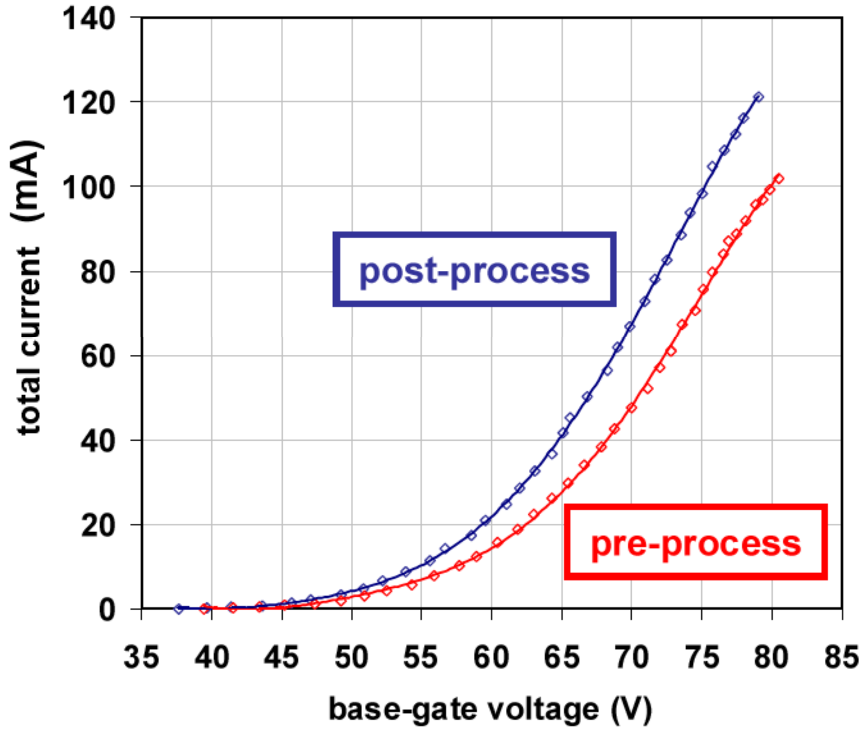
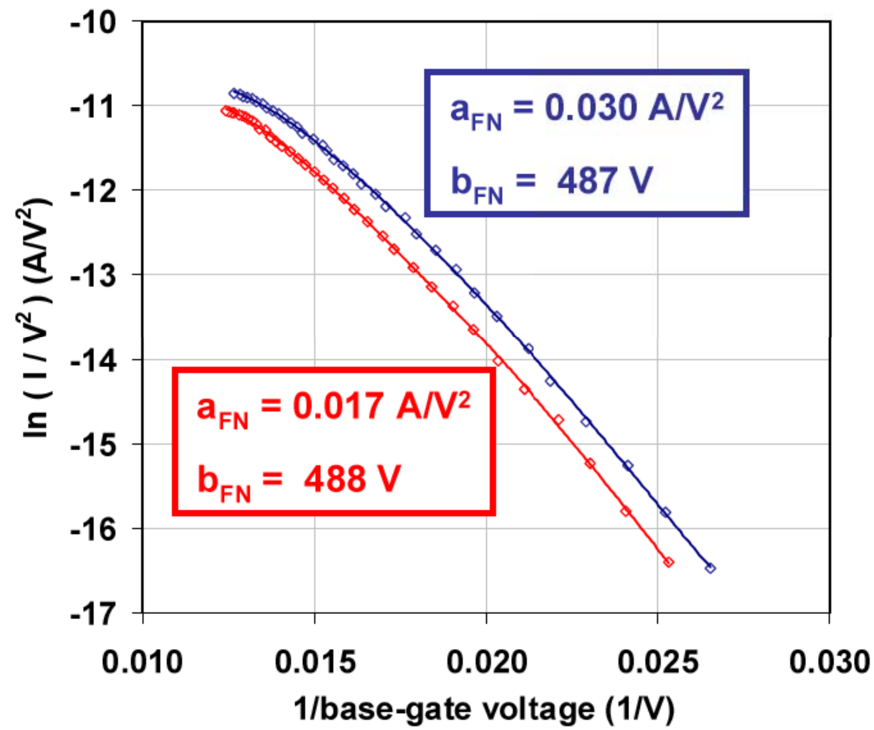


Experimental Results

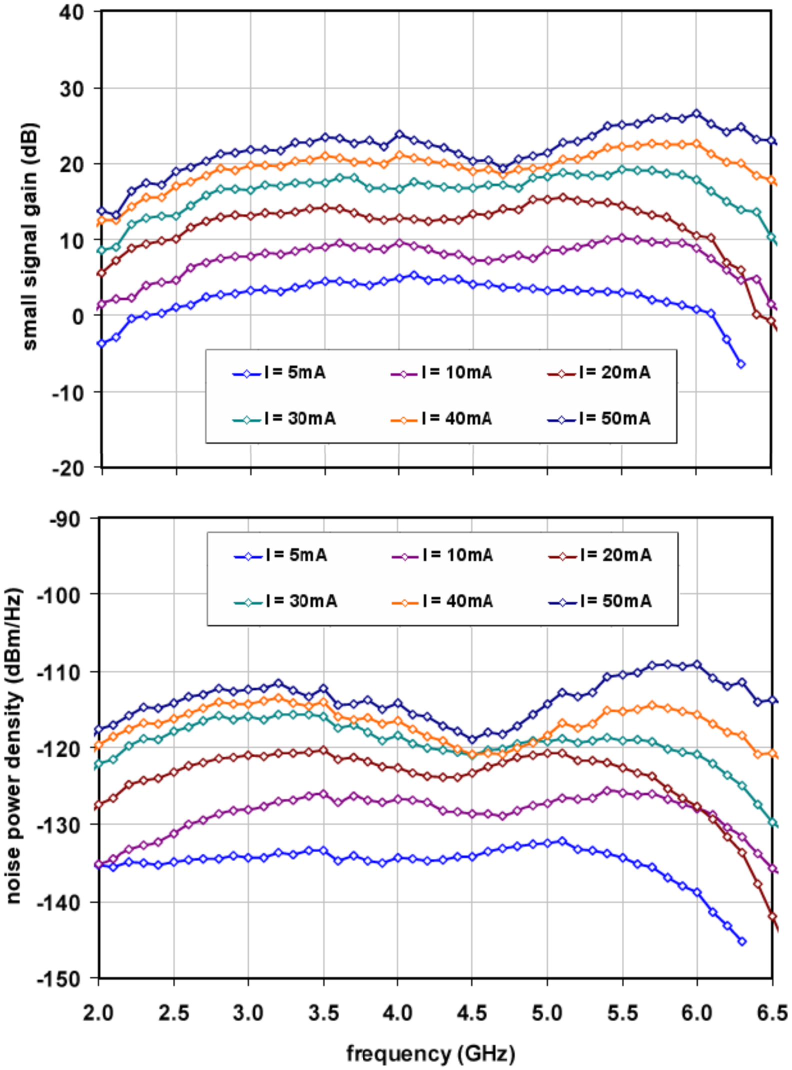
High Duty Processing



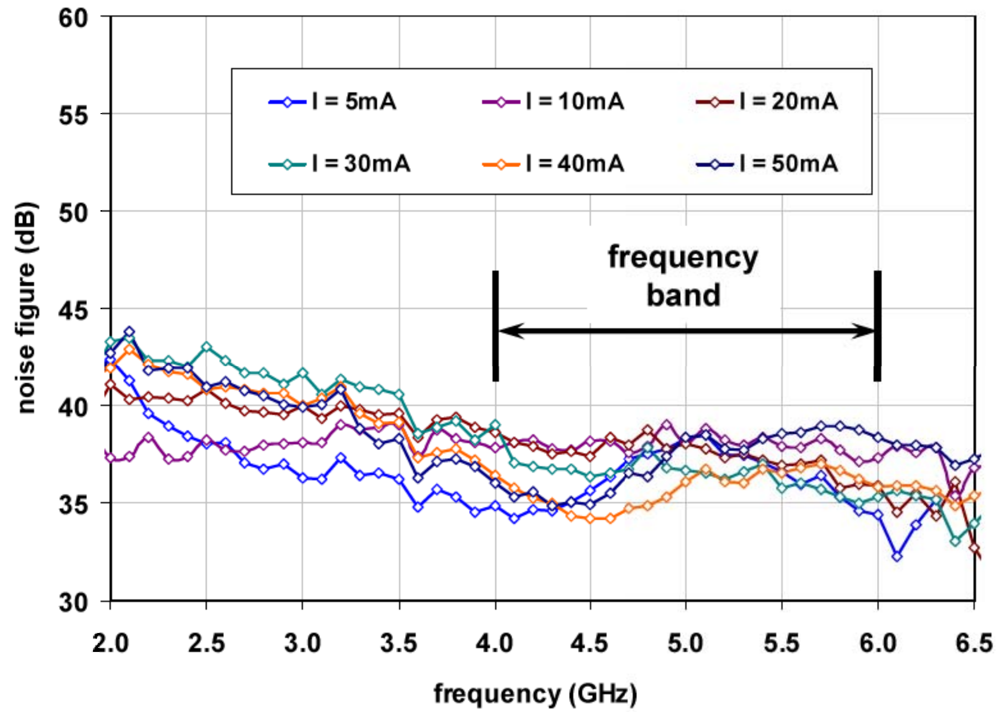


- High duty processing results in significant increase in a_{FN}, b_{FN} remains constant
- Implies that the active area of the cathode is increasing, work function unchanged
- Change appears to be permanent (time scale of weeks or longer)

Experimental Results



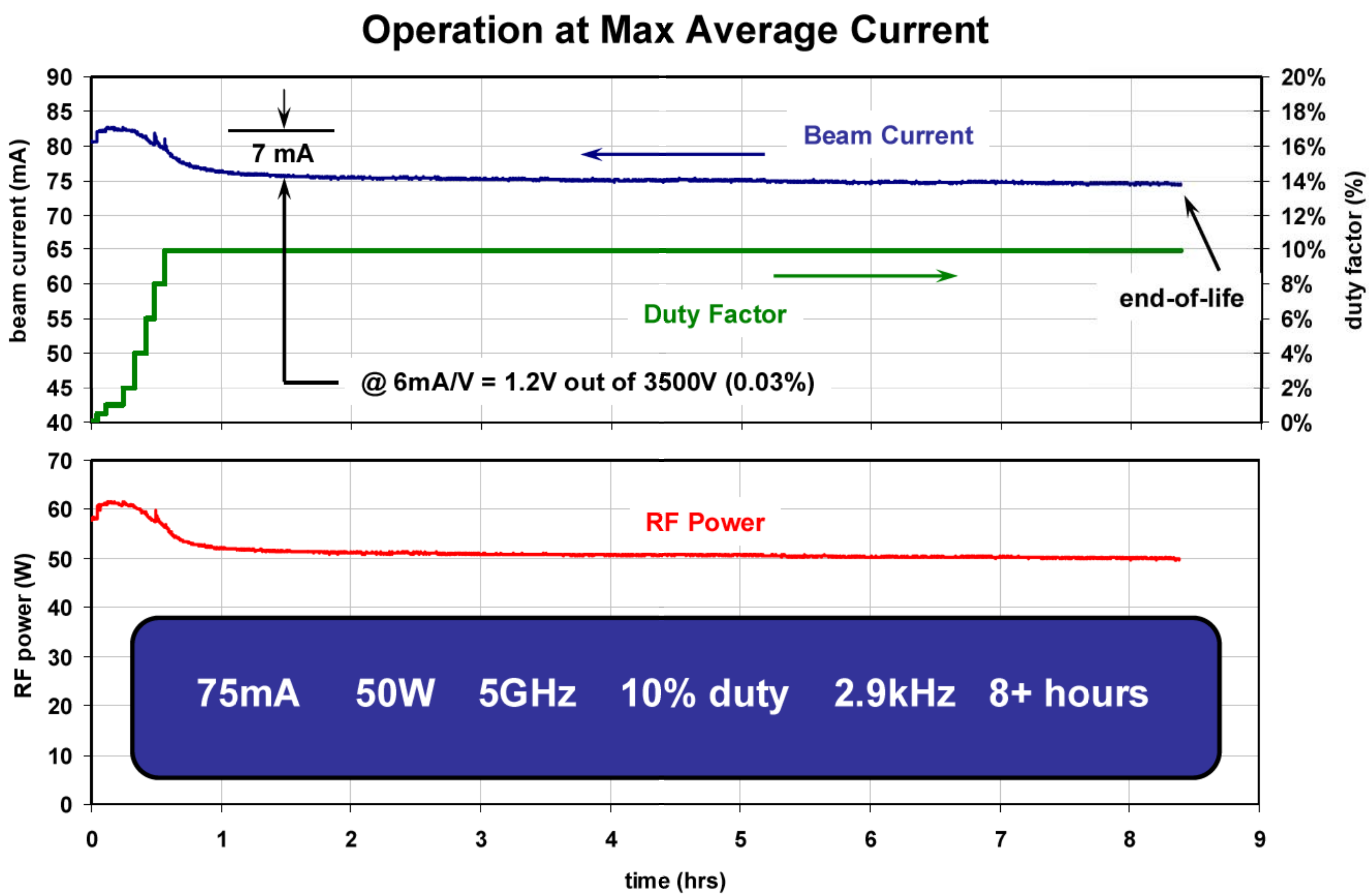
Noise Figure vs. Freq + Current



NPD = -174 dBm/Hz + G (dB) + NF (dB)

- In-band noise figure = 35-39 dB up to 50mA
- Improved method will replace thermal noise with calibrated noise source

Experimental Results



Conclusions

- Developed C-Band TWT specific for high current density field emitter array operation
- Demonstrated 72% cathode voltage reduction for full current operation
- Demonstrated TWT operation up to 120 mA, 15.4 A/cm^2, 100 W at 5GHz, 33dB ssg, 22dB sat gain, 24% circuit efficiency, 99% (97%) DC (RF) transmission
- Transconductance demonstrated at 8x that of legacy SRI FEAs
- Life tests conducted up to 100 mA (12.7A/cm^2) – 153 hrs total – 80mA at 10% duty highest average current
- Noise figure measured vs. current and frequency up to 50mA
- Time dependent changes in emission appear to be due to both cathode effective area increase and power supply variation with time
- Second cold cathode TWT built with modified operating characteristics for improved reliability

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